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# Heavy-Ion Fusion Final Focus Magnet Shielding Designs

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# Heavy-Ion Fusion Final Focus Magnet Shielding Designs

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ABSTRACT

At the Thirteenth International Symposium on Heavy Ion Inertial Fusion (HIF Symposium), we presented magnet shielding calculations for 72-, 128, 200, and 288-beam versions of the HYLIFE-II power plant design.[1-2] In all cases, we found the radiation-limited lifetimes of the last set of final focusing magnets to be unacceptably short.[1] Since that time, we have completed follow-on calculations to improve the lifetime of the 72-beam case. Using a self-consistent final focusing model, we vary parameters such as the shielding thicknesses and compositions, focusing length, angle-of-attack to the target, and the geometric representation of the flibe pocket, chamber, and blanket. By combining many of these shielding features, we are able to demonstrate a magnet shielding design that would enable the last set of final focusing magnets to survive for the lifetime of the power plant.

## I. INTRODUCTION

In previous work, we found that our point-of-departure final focus magnet lifetimes were unacceptably short.[1,3] In this work, we concentrate on improvement of the magnet lifetime for a self-consistent, 72-beam case. In Section II, we discuss the various shielding components and their effect upon the magnet lifetime. In Section III, we show results for cases in which multiple shielding features have been implemented in combined calculations. Section IV discusses three-dimensional effects in the flibe pocket, chamber, and blanket. Finally, in Section V, we draw conclusions from this work and suggest directions for future research.

In our estimation of the magnet lifetimes, we adopt two key limits: the maximum dose (the sum of the neutron and gamma doses is used) to the insulators and the maximum fast neutron fluence to the superconducting materials. At the beginning of this work, we used the dose limit of 50 MGy suggested by Sawan and Walstrom.[4] Recently, however, Tupper et al. suggest a higher value of 100 MGy for polyimides and bismaleimides.[5] Although these materials are more difficult to manufacture than epoxy insulators, it seems likely that more radiation resistant materials will be developed, and thus, we adopt the higher value.

For the fast ($E_n \geq 0.1$ MeV) neutron fluence limit, we adopt a value of $10^{19}$ n/cm$^2$ that is suggested for Nb-Ti in the review paper by Sawan and Walstrom.[4] This limit assumes a 70% recovery from room-temperature annealing following a fluence of $3 \times 10^{18}$ n/cm$^2$.[2,4]

## II. SHIELDING FEATURES AND RESULTS

The importance of many different shielding features was analyzed for the present work. We investigated, for example, the importance and cause of cross-talk between neighboring beams, the effect of shielding position, thickness, and composition, and the importance of magnet focusing length, beam stand-off, shielding provided by structural supports, and the areal density of the target.

### A. Cross-Talk

One interesting result from the HIF Symposium was the strong peaking of the fast neutron fluence observed in the center of the magnet array. Since this appears to result from a coupling between neighboring magnets, we dubbed the effect "cross-talk." Figure 1 shows the annual fast neutron fluence as a function of magnet rows and columns. The four corner magnets have an average result of $9.61 \times 10^{18}$ n/cm$^2$-y, but the centermost magnets have a fluence of $2.22 \times 10^{19}$ n/cm$^2$-y.

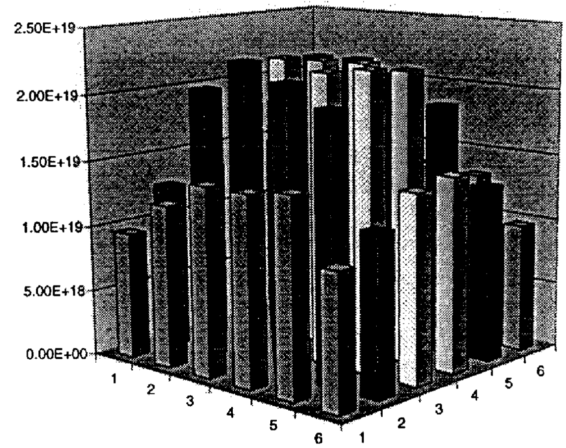


Fig. 1. Strong peaking of the annual fast neutron fluence (units are n/cm$^2$-y) is observed at the center of the array.

This, however, does not resolve whether the effect is due to the presence of neighboring magnets (scattering between magnets) or if the scattering occurs back in the flibe pocket (particles scattered into neighboring penetrations). To test this, we ran a case with only a single magnet and a single penetration. This case produced a fluence that was 8.7× lower than the average of the centermost magnets in the basecase. As a second test, we considered a case with a single penetration but we restored all 72 magnets. This increased the fluence by 24%—still 7.0× lower than the corner magnets in the basecase. We infer from these results that the important effect is scattering among the flibe pocket and between penetrations. The presence of neighboring magnets is a relatively small factor.

Given that scattering back in the flibe pocket seems to dominate the "cross-talk" effect and that high-energy neutron scattering is strongly forward-peaked, we investigated the array angle-of-attack to the target. In previous cases, magnets were packed as close as possible in order to minimize the array size. In doubling the angle between neighboring magnets, we found that the ratio between the fluence at the center of the array and at the corners fell to only 1.1, and the overall average fell by 1.9×. With a more modest angle increase of 50%, the overall average still fell by 1.7×—this seems to be a reasonable compromise between angle-of-attack and magnet lifetime.

B. Capture Zones

By using *capture zones* one can determine which parts of a problem have the greatest impact on the overall result. Whenever a particle enters a capture zone it is destroyed, and thus, may not reach a particular region to cause an effect. By studying capture zones we learned, for example, that the majority of the dose and neutron fluence reach the superconducting coils by way of the exterior banding. Use of a capture zone at the exterior of each magnet reduced the coil fluence by 5× and the total coil dose by 4×, while use of an interior capture zone reduced the fluence and total dose by 2.4× and 1.5×, respectively. As a result of these findings, subsequent calculations included both interior and exterior shielding. Finally, we found that frontal shielding can only reduce the dose to the superconductors by a factor of two.

C. Focusing Length

The distance from the center of the target chamber to the center of a final focusing magnet would appear to be an important consideration for shielding of the magnet. From a geometric point-of-view, however, we found the results to be relatively insensitive to the focusing length. The basecase assumed a focusing length of 5.5 meters. Making the focusing length 1 m shorter reduced the lifetime by 10-20%, while increasing the focusing length by 1 m increased the lifetime by only 2-8%. It should be noted, however, that these calculations account only for geometric factors—one could fill newly available space with additional shielding.

D. Shield Thickness and Composition

In an effort to further reduce the radiation effects to the magnets, we investigated the possibility of increasing the thickness of the inner bore shielding. Our results indicate that each 5 cm of tungsten shielding lead to roughly a factor of two reduction in both the fluence and total dose. Unfortunately, as is shown in Fig. 2, the solid-angle subtended by the overall array increases at close to the same rate. An increase in the array angle reduces the effectiveness of the thick-liquid shielding and pushes the final focus design beyond the angle compatible with currently available target designs. It is clear that simply adding more shielding is not an effective solution for accelerator designs with more beams than those in the past.

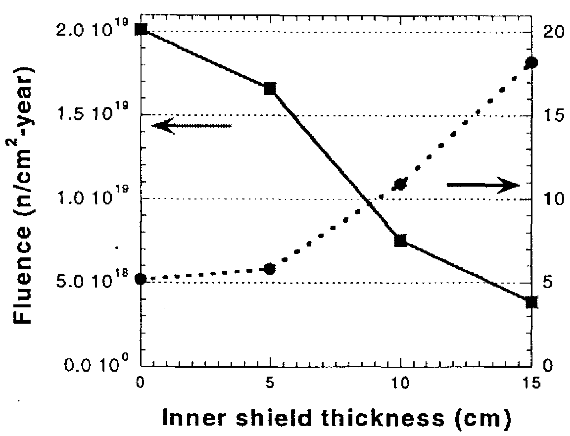


Fig. 2. The addition of inner bore shielding reduces the fast neutron fluence at the expense of the array size.

Because two criteria are being used to estimate the final focus magnet lifetime, a balance between the total dose to the insulator (dominated by gamma-rays) and the fast neutron fluence in the superconductor needs to be achieved. The basecase design, for example, results in a magnet lifetime prediction of 1.3 years based upon the total dose but only 0.6 years based upon the fast neutron fluence. By modifying the shielding composition, we seek a balance between these two effects.

A number of different shielding compositions were analyzed. Each design used 5 cm each of inner and outer bore shielding. Materials that were considered include tungsten, boron carbide, and three proprietary materials produced by Reactors Experiments, Incorporated: a tungsten impregnated-polyethylene, a titanium-hydride-polyethylene, and a tungsten/titanium-hydride polyethylene. Table 1 summarizes the results from eight different calculations that were completed to explore this parameter space.

Table I. Estimated magnet lifetimes for various shield compositions.

| | Magnet lifetime (years) based upon... | |
|---|---|---|
| Shielding material (inner/outer) | Total dose | Neutron fluence |
| 5 cm W each | 2.9 | 0.9 |
| 5 cm $B_4C$ each | 1.1 | 1.8 |
| 5 cm $B_4C$/5 cm W | 1.5 | 1.5 |
| 5 cm W/5 cm $B_4C$ | 2.0 | 1.3 |
| 4 cm $B_4C$ + 1 cm W each | 1.6 | 1.7 |
| 5 cm W-poly each | 2.0 | 2.6 |
| 5 cm Ti-hydride-poly each | 0.6 | 3.3 |
| 5 cm W/Ti-hydride-poly each | 1.5 | 2.8 |

At this point in our studies, we were still using a total dose limit for the insulators of 50 MGy. Based on that assumption, 5 cm of $B_4C$ inner bore shielding and 5 cm of tungsten outer bore shielding offers the best balance between the total dose and neutron fluence (but still a rather low lifetime). Later, however, we switched to the 100 MGy limit put forth in ref. 5. Based on this updated limit, the W/Ti-hydride-polyethylene would offer a good balance while extending the magnet lifetime to 2.8-3.0 years.

D. Beam Stand-Off Distances

It is impossible to place heavy-ion beams arbitrarily close to rapidly flowing liquids or even solid structural materials. The self-consistent final focusing design model assumes a beam pipe stand-off equal to 25% of the beam radius plus 5 mm. We initially assumed a stand-off of 5 mm between the beams and flibe jets or the shielding block. A smaller stand-off distance translates directly into more efficient collimation of radiation traveling up the beamlines towards the final focusing magnets. Figure 3 shows that elimination of the stand-off would reduced both the total dose and fluence by more than 2×. Increasing the stand-off from 5 mm to 1 cm would increase these metrics by ~ 1.8×. Additional work has shown that the key stand-off distance is the beam-to-structure stand-off distance; the stand-off from the beam to the liquid jets does not appear to be an important indicator of the magnet lifetime.

It is not clear at this time whether the stand-off distance can be reduced or even if it is adequate. Future work will seek to address this issue. For now, we will continue to use a 5 mm assumption.

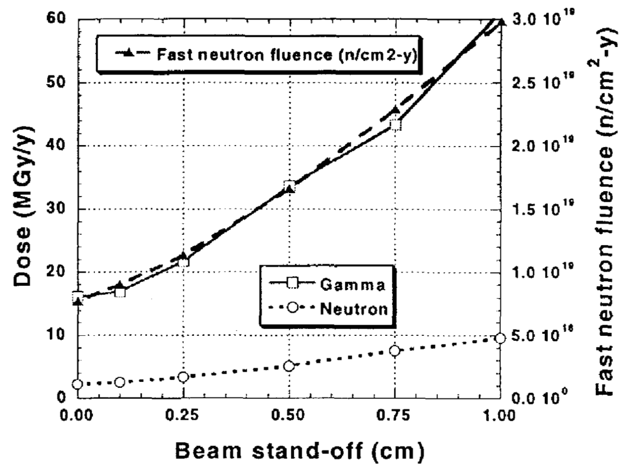


Fig. 3. Eliminating the stand-off between the beams and shielding would increase magnet lifetime by ~ 2.2×.

E. Other Effects

In the above calculations, the entire magnet array was modeled as if it was floating in space—no credit was taken for incidental shielding provided by the structural supports. Introduction of an "egg-crate" structure for support of the magnet array does, in fact, provide significant shielding benefits. Use of a boron carbide structure reduced the fast neutron flux by 40% and the total dose rate by more than 20%. Optimization of the egg-crate needs to be performed in concert with the rest of the shielding design.

The effects of the areal density ($\rho r$) of the target were not initially taken into account. For a $\rho r$ of 3 g/cm$^2$, we find that the fast neutron flux falls by 10%, while the total dose rate falls by 14% (13% for the gamma dose rate and 20% for the neutron dose rate).

III. COMBINED FEATURES

The next step in our analyses was to run several cases in which we combined various shielding features in an effort to increase the magnet lifetime. At the time when the combined cases were analyzed, we were still using a total dose limit of 50 MGy.

In the first combined case, we used a 6.5 m focusing length with the space between the back of the blanket and the magnets filled with borated water. Tungsten was used for both inner and outer bore shielding (5 cm each). A beam stand-off distance of 5 mm was assumed, and a boron carbide egg-crate was included. Based on the total dose, we predict an average magnet lifetime of 10.3

years. The fast neutron fluence, however, leads to a lifetime of only 2.9 years.

In the next calculation, we included the target ρr, used a more detailed model for the flibe pocket, removed the borated water, added 30 cm of tungsten-polyethylene shielding in front of the magnet array, and increased the spacing between magnets by 50%. The inner and outer bore shielding was maintained at 5 cm each, but the composition was altered to be 1 cm of tungsten and 4 cm of tungsten-polyethylene. The fluence-base lifetime increased slightly to 3.4 years, but the dose-based lifetime fell significantly to only 2.8 years.

The next calculation (case #3) used the same model as the second one with only a change to the frontal shielding. The thickness was increased from 30 to 120 cm and the composition went from tungsten-polyethylene to alternating layers of 10 cm tungsten and 20 cm of Ti-hydride-polyethylene. The dose-based lifetime rebounded to 6.8 years, and the fluence-based lifetime increased by 2.4× to 8.2 years.

We continued to try and reduce the fast neutron flux by switching the inner and outer bore shielding to Ti-hydride-polyethylene. The egg-crate was switched from $B_4C$ to tungsten to try and make back more of the dose-based lifetime. The fluence-based lifetime indeed increased to 9.9 years, but the dose-based lifetime fell again to only 3.9 years. This case was viewed as a failure, and we moved back to the design in case #3.

Case #5 was the same as case #3 except for the inner and outer bore shielding. Here, we layered the shielding to be 3 cm of tungsten-polyethylene sandwiched between two 1-cm-thick layers of tungsten. This case was quite successful with a balanced (from dose and fluence perspectives) lifetime of 14.1 years.

In the last of the "combined cases", we reduced the beam stand-off distances (to the solid structures and to the flibe jets) from 5 mm to only 1 mm. This resulted in well-balanced, long-lived magnets—31.7 years based upon fluence and 32.6 years based upon dose. The unknown here was whether or not one could manage to bring the beams so close to structures and liquids.

## IV. THREE-DIMENSIONAL MODELS

In all calculations described up to this point, the flibe pocket has been modeled using simple approximations. Additionally, the first wall and blanket were modeled using spherical shells. As a next step, these components were modeled in greater detail.

### A. Flibe Pocket

In the earliest calculations, the Flibe pocket was modeled as a 60-cm-thick spherical shell with conical penetrations. In the second combined case, this was improved to rectangular slabs that more closely resembled the intended liquid geometry. Finally, we switched to a 3-D model for the liquid geometry. The first 3-D model for the flibe pocket produced an average magnet lifetime of 71.6 years based upon the total dose rate and 84.6 years based upon the fast neutron fluence. We discovered, however, that the flibe pocket was not modeled in an adequate manner—it was too "leaky." Neutrons were scattered out of the cross-jet region, and the neutron activation of the first wall increased by a factor equal to the increase in the magnet lifetime.

To rectify this problem, we simply added additional flibe to the edges of the cross-jets. Figure 4 shows a cross-section through the liquid region; the improvement in the closed pocket design is easily seen. Figure 5 is a representation of the flibe pocket with the beam-paths shown as solid objects.

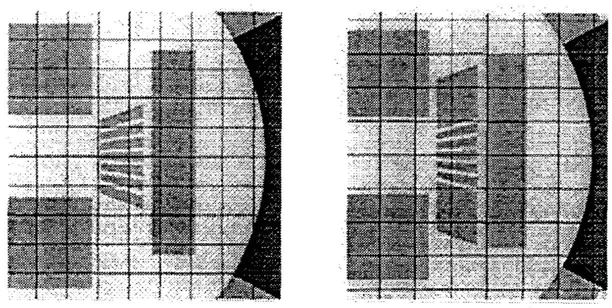

Fig. 4. Cross-sections through two versions of the flibe pocket—it is clear that the plot on the left is more "leaky" than the one on the right.

The 3-D representation of the flibe pocket results in improved shielding of the final focusing magnets. With simple shell or slab approximations, the pocket forms a near-perfect collimator and particles are forced towards the magnet array. With discrete jets, however, the flibe pocket allows particles to scatter out of the general direction of the magnet array. Despite this, first wall activation is as low as in the earlier calculations—the remaining parts of the flibe pocket scatter and/or capture the stray neutrons. The dose-based lifetime is 77.2 years, and the fluence-based lifetime is 96.9 years.

### B. Chamber and Blanket

The next step in the process was to use a more detailed model for the HYLIFE-II chamber and blanket. Figure 6 shows the final model that was created. Interestingly, the move to a detailed chamber/blanket model reduced the average magnet lifetime by ~ 30%.

The lifetimes are 56.1 years based upon dose and 65.9 years based upon fluence. This is believed to be due, in part, to geometric considerations. Although the solid-angle fraction is held constant, the actual wall area of the penetrations is larger for the 3-D chamber due to the angles above and below the equator of the cylindrical section. For the spherical shell, this effect does not exist—all beams strike the wall at the same distance from chamber center.

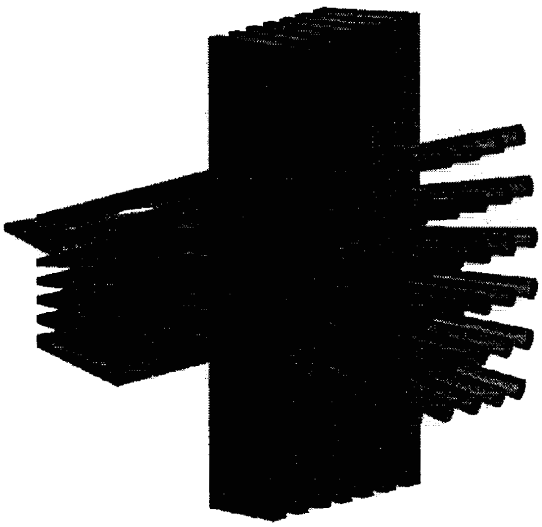

Fig. 5. The heavy-ion beams fit through the openings between horizontal and vertical flibe jets.

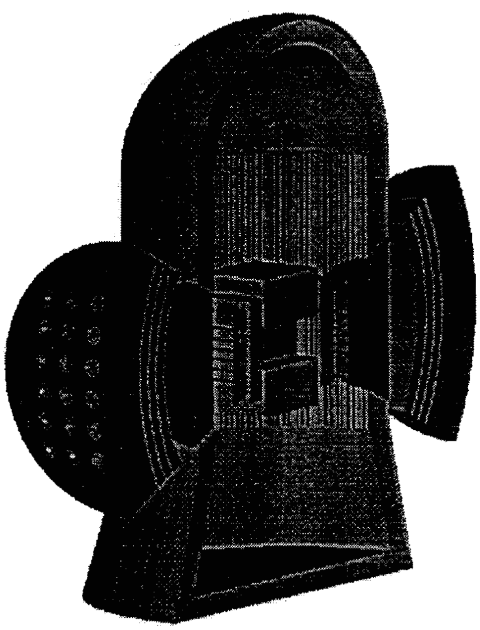

Fig. 6. The 3-D magnet shielding model includes many shielding features.

As the next round of calculations was completed, it became clear to us that the accelerator community was uncomfortable with our beam stand-off assumption of only 1 mm. We increased the stand-off back to 5 mm and repeated the 3-D calculations. We estimate lifetimes of 24.9 and 28.7 years from dose and fluence perspectives, respectively. At this point, it was also suggested that we increase our dose limit to 100 MGy.[5] This increases the dose-based lifetime to 49.7 years. If we modified the shielding to obtain a balance between the dose and fluence constraints, we would expect to obtain a lifetime of ~ 39 years—more than the expected power plant lifetime.

C. Cylindrical Cross Jets

One final set of calculations was performed for this work. Per Peterson of the University of California at Berkeley has proposed that the cross-jets should be made of cylindrical jets instead of rectangular slabs.[6] Potential advantages of cylindrical jets include less ripple (due to the ability to trim off the boundary layer) and the ability to use flow control of individual nozzles to correct for pointing errors.[6] Fig. 7 shows how the beams reach the target between the cylindrical cross-jets.

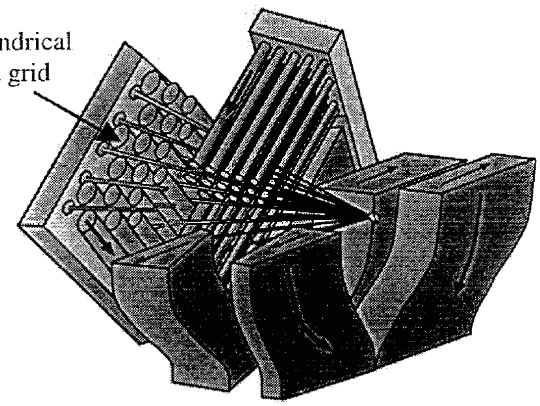


Fig. 7. The heavy-ion beams fit through the openings between horizontal and vertical flibe jets.

Our calculations show that cylindrical jets protect the magnets as well as rectangular slab jets. The dose-based lifetime is estimated at 51.1 years, while the fluence-based lifetime is 28.5 years. Achieving a balance between the total dose rate and fast neutron flux should yield a magnet lifetime of ~ 40 years.

## V. CONCLUSIONS AND FUTURE WORK

In the process of completing this work, several important conclusions have surfaced. One of the most important considerations in the calculation of the magnet lifetime is the stand-off distance between the heavy-ion beams and solid shielding structures. We will work with members of the accelerator community to understand the limitations in this parameter and determine what level of improvement is feasible.

Obviously, our results are only as good as our data. We will continue to work with members of the materials community to develop radiation-resistant insulators, stabilizers, and superconductors.

The models used in the present work have only included the last set of magnets. In previous work, backscattering from the other magnets was determined to contribute only 10% to the dose rate and flux at the last set of magnets.[3] In future work, we will include the additional magnets to ensure that our shielding modifications do not increase the importance of backscattering.

Cylindrical jet arrays appear to be quite attractive. We will complete additional assessments for cylindrical configuration that have higher liquid packing fractions.

Although our last shielding designs extend the magnet lifetimes to that of the overall power plant, they are inconsistent with current target requirements. Specifically, the angle of the magnet array is too large to meet the entrance angles for either the hybrid or close-coupled target designs. These designs are, of course, continuously being improved. The target designers are attempting to increase the angles, and we will try to reduce the radial build of the magnets to allow a smaller array angle.

We are working with the other stakeholders to develop a self-consistent design for the final focusing system. This design must meet the thermal hydraulics constraints while satisfying target, accelerator, economics, and, of course, shielding requirements.

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